Effects of HVDC Connection for Offshore Wind Turbines on AC Grid Protection

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***Abstract*—When a transmission line close to points of common coupling (PCCs) encounters a short circuit (SC), the resulting PCC voltage dip triggers fast reactive power control of the corresponding grid side voltage source converter (GSVSC) to boost the PCC voltage. The control action can cause the fault distance to be overestimated by its backup relay located on the adjacent line. It is possible for a Zone 2 fault to be viewed as a Zone 3 event, resulting in mis-coordination between protective relays. Numerical simulations demonstrate the effect of HVDC offshore wind network on distance protection of an ac grid. On the other hand, HVDC reactive power adjustment can increase the stability margin of onshore ac grids, as shown by contingency simulations. With the addition of HVDC-connected offshore wind turbines, the voltage source converter based HVDC (VSC-HVDC) control can function as an element of the overall power system defense plan to prevent system instability, reducing or avoiding the implementation of the last resort remedial option – load shedding.**

***Index Terms*—VSC-HVDC, offshore wind farms, distance relays, defense plan, decoupling control of VSC, system stability.**

I. Introduction

DURING the last decade, the penetration of renewable energy, including offshore wind turbines, has increased dramatically in order to achieve an overall reduction of green house gas emissions. A report from European Wind Energy Association (EWEA) has shown that the installation capacity of EU offshore wind units will be increased to 150 GW by 2030 as additional generation resources to meet 14% of the EU electricity demand [1]. The rapid growth of offshore wind power and its inherent characteristics (e.g. large scale and long distance) make the integration of offshore wind power to onshore ac grids a great challenge. With the innovation of transmission technologies, the VSC-HVDC technology has shown its advantages to overcome limitations of the conventional ac transmission technology for offshore wind power integration. The typical advantages of the VSC-HVDC technology include fast and independent control of active and reactive power, feasibility of multi-terminal dc grids, and black start capability [2]-[3]. In a HVDC offshore wind network, the function of the HVDC connection is to collect offshore wind power and deliver it to onshore ac grids. Generally, the wind farm side VSC (WFVSC) adjusts the magnitude and frequency of the wind farm terminal voltage to enable the collection of all offshore wind power. The GSVSC is used to control the dc link voltage. A constant dc voltage can automatically balance the sending end and receiving end active power of the HVDC. In addition, the GSVSC also allows reactive power support for onshore ac grids to maintain the PCC voltage at a pre-determined level.

When the PCC experiences a voltage dip during a nearby SC fault, the transmission capability of the HVDC is reduced. Since the offshore wind power received by the WFVSC cannot be decreased instantaneously, the resulting power imbalance in the dc link causes dc capacitors to be charged, leading to a dramatic increase of the dc voltage [4]. It has been shown that the installation of dc choppers can effectively dissipate unbalanced power and protect dc transmission devices.

In addition, the HVDC control can significantly affect the fault performance of onshore ac grids. Due to the constant ac voltage control mode, the GSVSC reactive power control is activated to boost the PCC voltage during the SC fault. This tends to impact bus voltages and line currents close to the PCC. Generally, the capacity of VSC stations is expected to be large for bulk offshore wind power transmission. The resulting effect of reactive power on the performance of ac protection schemes can be significant. Distance protection is a good example. The basic principle of distance protection is based on the apparent impedance measurement that determines the approximate distance between the relay location and fault point during a SC fault [5].

Most reactive power compensation devices are based on the full-controlled power electronic switch technology, such as static var compensators (SVCs) and static synchronous compensators (STATCOMs). The technology allows devices to fast regulate reactive power exchange with ac grids. It has been discussed in existing studies that fast reactive power adjustment can affect the performance of distance relays on ac grids. The study in [6] evaluates the performance of distance relays on the transmission lines equipped with SVC and STATCOM shunts, respectively. In addition, the work of [7] focuses on reactive power adjustment of unified power flow controllers (UPFCs) and analyzes its impact on distance relays located on the UPFC terminal buses. Compared with these

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flexible alternating current transmission (FACTS) controllers, VSC stations provide a much higher capability of reactive power adjustment. The resulting effect on the operation of distance relays needs to be addressed.

With the addition of HVDC-connected offshore wind turbines, more control options from the HVDC are provided to enhance the stability of onshore ac grids, such as multi-HVDC active power regulation and reactive power support. They can be applied to damp system oscillations and increase the stability margin. In severe situations, the available HVDC control may prevent system instability and reduce or avoid load shedding. In contrast with conventional ac grids, a higher level of control capability can be provided by the ac grid with HVDC-connected offshore wind turbines for the design of system protection schemes that is intended to reduce the impact of severe contingencies.

The organization of this paper is as follows. Section II outlines an 'H' shaped HVDC offshore wind network. Section III analyzes the effect of HVDC control on distance relays of the ac grid. Numerical simulations with the IEEE 39-Bus system are performed to demonstrate the possible mis-coordinated operation of distance relays with the proposed HVDC offshore wind network. Based on contingency analysis, Section V highlights the potential opportunities brought by HVDC-connected offshore wind turbines for the design of system protection schemes.

II. System Configuration

A. HVDC Offshore Wind Network

Fig. 1 illustrates the configuration of a HVDC offshore wind network. Two offshore wind farms based on doubly fed induction generators (DFIGs) are connected to an onshore ac grid through an 'H' shaped HVDC connection. Two WFVSCs are controlled to collect the generation of offshore wind farms and convert it to dc power. Two GSVSCs are used to deliver the received dc power to the onshore ac grid. Due to the large scale of offshore wind farms, the HVDC connection for wind power transmission is expected to be connected to the transmission levels of onshore ac grids.

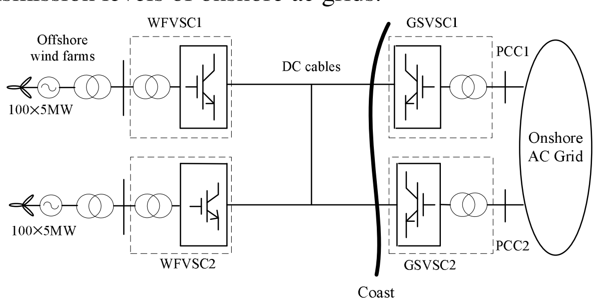

Fig. 1 'H' shaped HVDC Offshore wind network

B. VSC-HVDC control

In the multi-HVDC network, both WFVSCs apply the constant ac voltage and frequency control mode that enables the collection of all offshore wind power. The simplified control configuration of WFVSCs is shown in Fig. 2. Offshore wind farms are modeled as voltage sources with a closed-loop controlled magnitude (v_{wf}), constant frequency (f) and phase angle (θ). M is the modulation index of PWM control of WFVSCs. The subscript "*_ref*" is used to indicate the reference value.

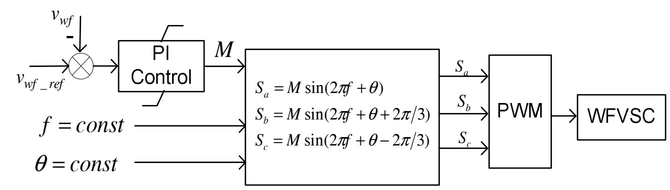

Fig. 2 Simplified control configuration of WFVSCs

Fig. 3 shows the GSVSC control configuration. The dc grid voltage is adjusted by the power-voltage droop that determines the power flow distribution of the dc grid. It can be represented as

$$v_{dc\_ref} = v_{dc} + k(P - P_{ref}) \tag{1}$$

where v_{dc} is the dc side voltage of a GSVSC, P is the active power transmitted by the GSVSC, and the symbol k is the slope of the power-voltage droop characteristic curve.

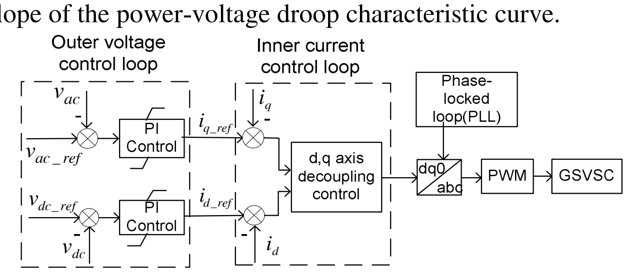

Fig. 3 Simplified control configuration of GSVSCs

Applying d,q-axis decoupling control, GSVSCs can independently regulate their reactive power output to maintain the corresponding PCC voltage (v_{ac}) at an expected level. As shown in Fig. 3, the error between the reference and measured PCC voltage is used to control the q-axis component of the GSVSC ac side current that determines the GSVSC reactive power output. When a PCC experiences a voltage dip during a disturbance, say, SC, the corresponding GSVSC control is activated to provide reactive power to boost the PCC voltage. With the high frequency switching technology, the time constant of the VSC control can be in the order of tens of milliseconds, much faster than that of excitation systems of conventional synchronous generators.

III. Distance Protection of AC Grid

A. Distance Protection of AC Grid

The distance relay is a widely adopted protective device that is designed to provide the primary and backup protection of transmission lines. Zone 1, as the primary protection, is required to protect 80%-90% of the line length without an intentional time delay. Zone 2 functions as a backup protection and its protection range reaches 40%-50% of the shortest line emanating from the remote bus. A time delay (typically 15-30 cycles) is applied to coordinate with Zone 1 relays [8]. In some of ac grids, Zone 3 is utilized to offer a remote backup protection that is required to exceed adjacent lines with the typical time delay of 1 s [5]. The operation of distance relays is determined by the pre-set operational characteristics.

B. Discussion of Impact of GSVSC Control on Distance Relays

Fig. 4 shows a portion of an ac grid with a converter (GSVSC2). When line j-k experiences a three-phase SC fault F, it is viewed by relay B as a fault in Zone 1. Assuming the fault impedance is 0, the impedance viewed by relay B is the line impedance from the fault point to the relay location. In case of a failure of Zone 1 relay, say, relay B should operate but it does not, the isolation of fault F will rely on its backup protection - relay A that is located on the adjacent line i-j. The apparent impedance viewed by relay A can be obtained as

$$Z_{m\_A} = \frac{V_i}{I_{ij}} = \frac{V_j + Z_{ij} * I_{ij}}{I_{ij}} = \frac{V_j}{I_{ij}} + Z_{ij} \qquad (2)$$

where V_i and I_{ij} are the voltage and current viewed by relay A, respectively. V_i is represented as a function of the PCC2 voltage (V_j) by applying the Kirchhoff's voltage law. Z_{ij} is the impedance of line i-j that is a constant. Therefore, the impedance viewed by relay A, i.e., Z_{m_A}, is determined by the PCC voltage and its apparent current.

Compared with the excitation systems of synchronous generators, the GSVSC reactive power regulation demonstrates a much faster dynamic response. During fault F, GSVSC2 is triggered to provide reactive power support to boost the reduced PCC2 voltage. The resulting PCC2 voltage increase leads to a reduced current on line i-j. As a result, the impedance viewed by relay A is increased and the fault distance viewed by relay A is overestimated. It is therefore possible for a Zone 2 fault to be viewed as a Zone 3 event. The resulting delay of the fault clearance can reduce the margin of system stability, endangering system security under severe conditions.

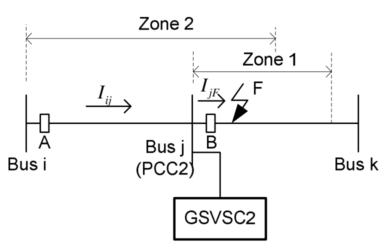

Fig. 4 Portion of ac grid with a converter

C. Simulation System

The IEEE 39 bus system shown in Fig. 5 is modeled in DIgSILENT PowerFactory for distance protection analysis. Both ends of transmission lines are equipped with impedance relays. Their Zone 1 protects 80% of the line length. Zone 2 of distance relays is set to reach 50% of the shortest line emanating from the remote bus with the time delay of 22 cycles, i.e., 0.37 s in the 60 Hz system. The detailed settings are identified by fault simulations in DIgSILENT PowerFactory. The identification method of the Zone 2 setting of a relay, say, relay A, is shown as follows:

(1) Initiate a three-phase SC fault at 50% of line 23-24 at 0 s;

(2) Measure the apparent impedance viewed by relay A at 0.37s and set it as the Zone 2 setting of relay A.

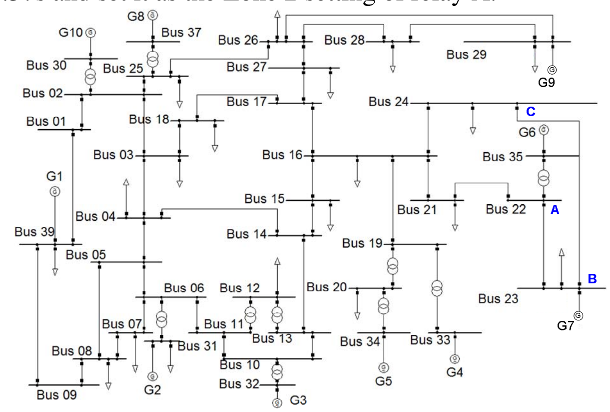

Fig. 5 IEEE 39 bus system

The proposed 'H' shaped HVDC offshore wind network is connected to the IEEE 39 bus system. GSVSC1 and GSVSC2 are connected to buses 29 and 23 to replace G9 and G7, respectively. The 'H' shaped HVDC connection consists of four 600 MVA, ± 150/132 kV VSCs. The current limit of converters is set to 1.25 p.u.. The integrated ac/dc system is modeled in the DIgSILENT PowerFactory. The scenarios of the integrated ac/dc system are adjusted to ensure identical power results the IEEE 39 bus system. For comparison purposes, an identical fault is simulated on both systems, i.e. the IEEE 39 bus system and integrated ac/dc system, for the identification of HVDC impact on ac distance protection. Simulation results are reported in Section III D.

D. Case Studies

A three-phase SC fault K with zero fault impedance is located at 15% of line 23-24 in the IEEE 39 bus system, as shown in Fig. 6 (a). According to the fault location, fault K is in the range of Zone 1 of relay B, and Zone 2 of relay A. In case Zone 1 of relay B should operate but it does not, Zone 2 of relay A on line 22-23 functions as a backup protection to isolate fault K. The trajectory of the impedance viewed by relay A (the arrowed line) is shown in Fig. 6 (b), where black circles are the operational characteristics of relay A. It is found in Fig. 6 (b) that the impedance viewed by relay A enters the Zone 2 area, when fault K is initiated. After a Zone 2 time delay, Zone 2 of relay A is activated. The tripping of circuit breaker A leads the impedance viewed by relay A to exit the relay A zones. It is obtained that relay A activation is correctly triggered with the Zone 2 time delay to isolate fault K.

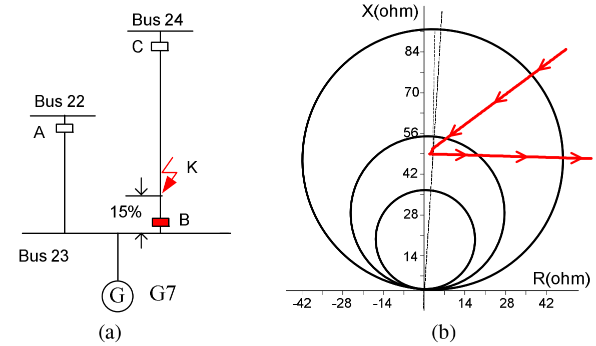

Fig. 6 (a) SC fault location on the IEEE 39 bus system; (b) Trajectory of relay A on IEEE 39 bus system

An identical SC fault K is simulated in the integrated ac/dc system, i.e., the IEEE 39 bus system with HVDC offshore wind network, as shown in Fig. 7 (a). The fault location shows that fault K should be in Zone 2 of relay A. Relay A has the identical settings with that in the IEEE 39 bus system. For a Zone 1 failure of relay B, the trajectory of the impedance viewed by relay A is shown in Fig. 7 (b). In contrast to the trajectory shown in Fig. 6 (b), the impedance viewed by relay A enters Zone 3 rather than Zone 2, when fault K is initiated. Namely, fault K is judged to be a Zone 3 event of relay A in the integrated ac/dc system. Fault K is isolated by the tripping of relay A after a Zone 3 time delay, leading to protection mis-coordination.

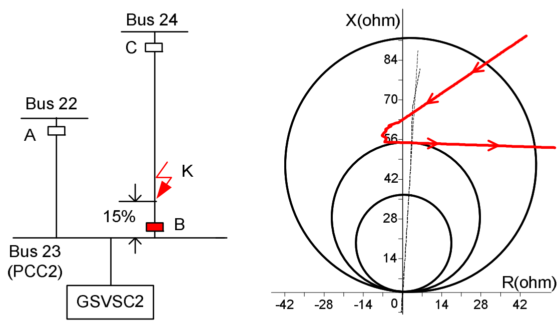

Fig. 7 (a) SC fault location on the integrated ac/dc system; (b) Trajectory of relay A on the integrated ac/dc system

It is found that the connection of the HVDC offshore wind network results in fault K being falsely judged to be a Zone 3 event of relay A. Fast reactive power control of the HVDC connection affects the performance of nearby bus voltages and line currents during fault K. The effect can lead to confusion of relay operations, resulting in protection mis-coordination. Note that the fault distance viewed by a relay will be overestimated in cases where fast-response reactive power compensation devices are located between the fault point and relay location.

The conventional excitation voltage control of synchronous generators demonstrates a much slower dynamic during disturbances. During the time delay of Zone 2, the slow dynamics do not contribute to the generator terminal voltage adjustment due to its higher time constant (about 0.5 s). Therefore, relay A in the IEEE 39 bus system performs a correct operation during fault K, as shown in Fig. 6 (b).

In both simulation cases, the activation of distance relays independently relies on their apparent impedances and operational characteristics, without any communications. Since the fault impedance is 0, the impedance viewed by relay C is the line impedance from the fault point K to relay C location. Therefore, the addition of the HVDC offshore wind network does not impact the performance of relay C.

IV. System Protection of AC Grid

A. SPS and Defense Plan

A special protection scheme (SPS) is a mechanism designed to detect abnormal system conditions and to take predetermined actions to avoid power system instability. Its function is distinct from the usual protection scheme that individually isolates a faulted component from power grids. In the early stage, SPSs are developed for the specific scenarios under the given operating condition. With increasing complexity of power systems, the concept of a defense system has been recognized as an emergency control system against cascading events that can lead to a catastrophic outage of power grids. In contrast with SPSs, a defense system is intended to provide a line of defense based on the system operating condition in response to a disturbance to prevent a system collapse [9-10]. Individual SPS is regarded as a coordinated element of a defense system.

In the last decade, costly large-scale outages have occurred in Europe, such as Italy/Switzerland in 2003, Greece in 2004, Sweden in 2005 and Central Europe in 2006 [11]. To minimize the potential risk of widespread outages, major power grids have developed and implemented defense systems, such as EDF (France) and TERNA (Italy). With the penetration of offshore wind power, flexible and fast control of the added VSC-HVDC connections can play a significant role in providing regulation options for the design of defense plans.

B. Case Studies

The simulation is based on the assumption that offshore wind farms experience a wind power deficit due to an event, say, decreasing wind speed or tripping of a faulted element, that leads to reduction of the offshore wind farm output by 600 MW. Under this condition, a three-phase SC fault is initiated on line 23-24 at 0 s and the faulted line is cleared by its circuit breakers after 0.1 s. The measured frequencies on main buses and voltages of buses close to the reference generator (G2) during disturbances are shown in Fig. 9. It is found that the integrated ac/dc system can provide sufficient damping to maintain system stability following disturbances.

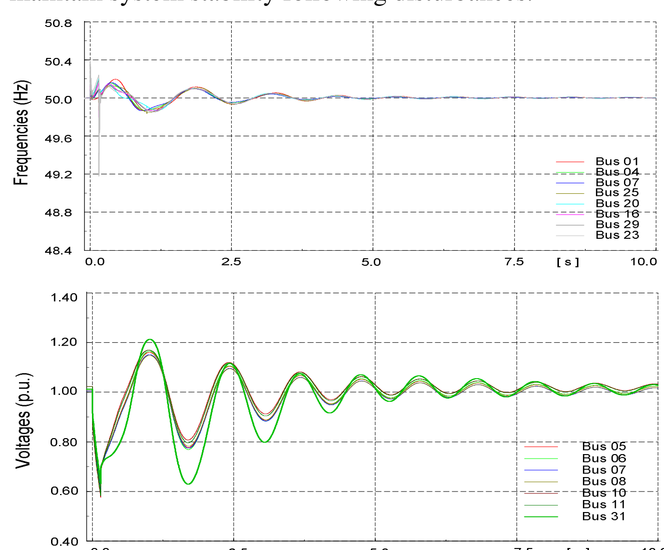

Fig. 9 Simulation results of integrated ac/dc system during disturbances

The identical fault is simulated on the IEEE 39 bus system that is set to have identical power flow results with the integrated ac/dc system under the wind power deficit. As shown by simulation results in Fig. 10, generators in the IEEE

39 bus system are not operating in synchronism. At about 1.5 s, voltages dramatically decline with larger dips than that in Fig. 9, especially for the slack bus 31. It forces synchronous generators to increase their output to achieve system power balance. This leads to an instantaneous increase of the generator electrical torque, which is not balanced by the generator mechanical torque instantly due to the high mechanical inertia. The resulting torque difference in turn increases the generator rotor speed. When the rotor electrical angle exceeds its operation limit, synchronous generators cannot be operated in synchronism.

As one of the most common and effective remedial control schemes, load shedding may be needed to prevent system instability by achieving a new power balance in the IEEE 39 bus system. According to the comparison of simulation results in both systems, it can be found that the addition of the VSC-HVDC grid results in lower voltage dips that prevent synchronous generators from swinging out of step, avoiding the implementation of the last resort remedial control option – load shedding.

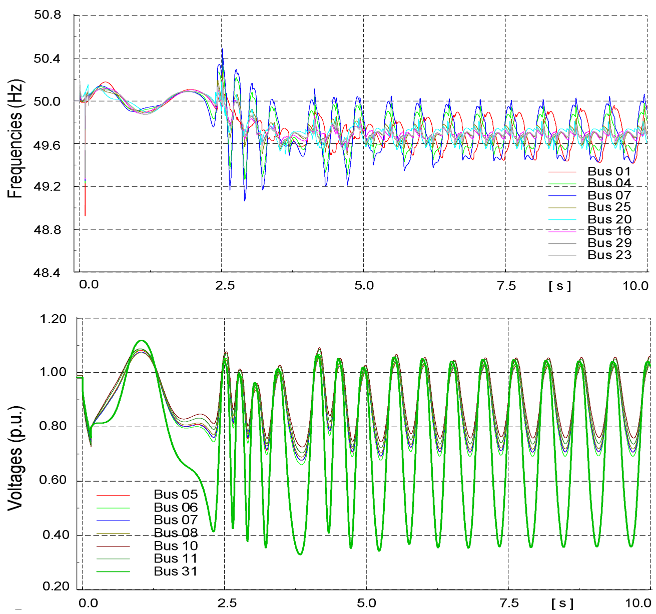

Fig. 10 Simulation results of IEEE 39 bus system during disturbances

V. Conclusion

With the increasing penetration of offshore wind power, a significant addition of VSC-HVDC links will be connected to ac mainland grids. The potential effects of VSC-HVDC control discussed in this paper include line distance protection and stability protection:

(1) Due to HVDC fast reactive power adjustment, the fault distance of a SC fault can be overestimated by its backup relay located on the adjacent line. Numerical simulations in this study demonstrate possibilities of a Zone 2 fault being viewed as a Zone 3 event. The resulting protection mis-coordination may endanger system security;

(2) In addition, simulation results indicate that the available HVDC control can play the role of a system protective function to reduce the impact of contingencies. For the future integrated network, it will be significant to consider HVDC control in the development of defense plans.

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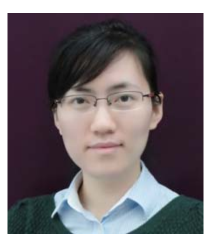

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